

Tectonics and Water on Europa

Europa, the satellite of Jupiter, probably hosts a subsurface water ocean but the thickness of the outer ice crust is poorly constrained and the role of liquid water in its complex tectonics is debated. We argue that some surface features are formed by soft ice heated by viscous dissipation of tidal motion along faults and do not require a shallow ocean. Our model does suggest that transient pockets of liquid water or brine could form at shallow depths in the crust.

High-resolution images of surface lineations and ridges on Europa returned by the Galileo spacecraft have motivated proposals that tidal stresses from Jupiter fracture the icy crust of the synchronously-rotating satellite and allow material from the interior to reach the surface^{1,2}. One such model invokes tidal expansion and contraction of meter-wide cracks that repeatedly force liquid water from a subsurface ocean to the surface as the satellite completes each 85-hour orbit³. This mechanism requires that the ice shell is thin (1 km or less) and has fuelled speculation that the ocean makes frequent contact with the sunlit surface and could be a habitat for life. However, the formation of km-deep cracks in Europa's crust is problematic. Below a depth of 35 m the pressure from the weight of the overlying ice will exceed the estimated stresses due to tides ($< 4 \times 10^4$ Pa) and prevent crack growth. Secondly, any fractures will halt at a depth where warmer, less viscous ice will flow, rather than fracture, to accommodate tidal strain. Taking an estimated strain rate of $2 \times 10^{-10} \text{ sec}^{-1}$ and a relation between normal stress and yield stress appropriate for ice⁴ we find the brittle-ductile transition to occur at depths where temperatures⁵ exceed 170 K, i.e., well above any ice-ocean interface. Finally, liquid water in a crack will freeze solid by conduction of heat to the walls: The freezing time is $t = w^2 / (16\kappa\lambda^2)$, where w is the crack width, κ is the thermal diffusivity of ice ($1.7 \times 10^{-6} \text{ m}^2 \text{ sec}^{-1}$) and λ is a dimensionless parameter⁶ equal to about 0.3. A one-meter crack will freeze in 1.3

orbits. Hydrostatic forces are too weak to extrude ice from such a narrow orifice and unless a compensatory removal of crust occurs elsewhere, the crack will disappear.

We propose an alternative scenario where tides drive viscous flow and heating by dissipation at zones of lateral motion (strike-slip) in the crust. There is accumulating evidence for strike-slip motion on Europa⁷. The relative motion along a fault or defect will produce frictional heating, causing the local temperature to increase and the viscosity of the ice to decrease⁸. This feedback can lead to accommodation of the relative motion of two blocks of crust by viscous flow in a zone of finite width rather than a discontinuity at a fault. Steady-state conditions in the zone are derived by equating the production of heat by viscous dissipation with its loss by conduction to the surrounding ice. Strike-slip motion of amplitude a at a diurnal period t (3×10^5 sec) will maintain a temperature T_c and viscosity η_c at the center of the shear zone⁶ which satisfy $16kRT_c^2 t^2 = \pi^2 \eta_c E_a a^2$, where E_a and k are the activation energy (6×10^4 joules at 273 K) and thermal conductivity ($2.1 \text{ watts m}^{-1} \text{ K}^{-1}$ at 273 K) of the ice, and R is the gas constant ($8.314 \text{ joules K}^{-1} \text{ mole}^{-1}$). A plausible diurnal motion³ of 0.6 m can maintain the ice in the center of the zone at a temperature of 273K where its viscosity will be roughly 10^{13} Pa-s . The width of this zone of soft ice is $\delta = \eta \tau^{-1}$, where τ is the shear stress, and is about 1 km for $\tau = 2 \times 10^4 \text{ Pa}$. This warm ice will have a buoyant density contrast $\Delta\rho = 20 \text{ kg m}^{-3}$ with respect to the surrounding ice and will flow upwards by a few tens of cm over the course of one tidal cycle. We conjecture that such motion over the course of many cycles could form structures such as the ridge pairs. Our model does require the existence of an ocean (not necessarily shallow): Without the mechanical decoupling between the ice crust and the interior the motion of the crust would be 30-50 times smaller.

Larger strike-slip motion may lead to partial melting (liquid water) in the shear zone. The melt generation rate scales as $\tau^2 (\rho \eta_c L)^{-1}$, where L and ρ are the latent heat of fusion (3.25

$\times 10^5 \text{ joules kg}^{-1}$) and density (900 kg m^{-3}) of ice. This production will be balanced by downwards percolation of the denser melt at a rate⁹ $A\phi^n \Delta\rho g (\eta_m h)^{-1}$ where A and n are constants, ϕ is melt fraction, η_m is melt viscosity, h is the thickness of the melt column, and g (1.3 m sec^{-2}) is Europa's surface gravity. Although there are considerable uncertainties in some of these values, the equilibrium melt fraction is of order 1%. This much melt will form only if the strike-slip motion is sufficiently large ($\sim 1 \text{ m}$) to compensate for the reduction in ice viscosity by a factor of about one third due to the presence of melt¹⁰. The pore pressure due to the presence of melt will also increase the depth to the brittle-ductile transition and allow fractures to accommodate strike-slip motion and slow the generation of heat. Melt pockets below the fracture zone will percolate downwards at a velocity of a few tens of meters per year and thus will have a lifetime of ~ 1000 years. Any melt at the base of the fracture zone will escape through the fractures or freeze and if salts are present, brines will be rejected from the freezing melt¹¹. Here, the melt lifetime, estimated by equating the latent heat that must be rejected to the rate of thermal conduction away from the fault zone, will be $\sim 30 \text{ yr}$ (shorter at shallow depths where vertical conduction to the surface is important). Depending on the thickness of the fractured zone, transient liquid water or brine pockets may exist within reach of sunlight. These could be potential habitats for photosynthetic organisms capable of remaining dormant in ice for millennia¹² between relatively brief "blooms".

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